

# **Remote Sensing and in situ Observation of Internal Wave Generation in the Luzon Strait**

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## **LONG-TERM GOALS**

Our long-term goal is to locate the source of non-linear internal waves (NLIWs) in the northern South China Sea (SCS), study their generation mechanism and establish the capability to predict its generation time and propagation path.

## **OBJECTIVES**

In 2005, locate NLIWs with satellite image analysis and field data collection, and study their characteristics. In 2006, study the evolution of NLIWs from internal tide. In 2007, study their generation mechanism, and derive a model to predict their generation and propagation.

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## **APPROACH**

The objective of 2006 is approached by analysis of various satellite images, by field observation, by cross analysis of satellite and field data, and by numerical simulation of NLIW generation and propagation. Members of our team share the work in collecting satellite and field data, in analyzing these data to study ocean dynamics, in collecting and analyzing the surface wave data, and in numerical simulation of the evolution internal waves.

The project tasks include:

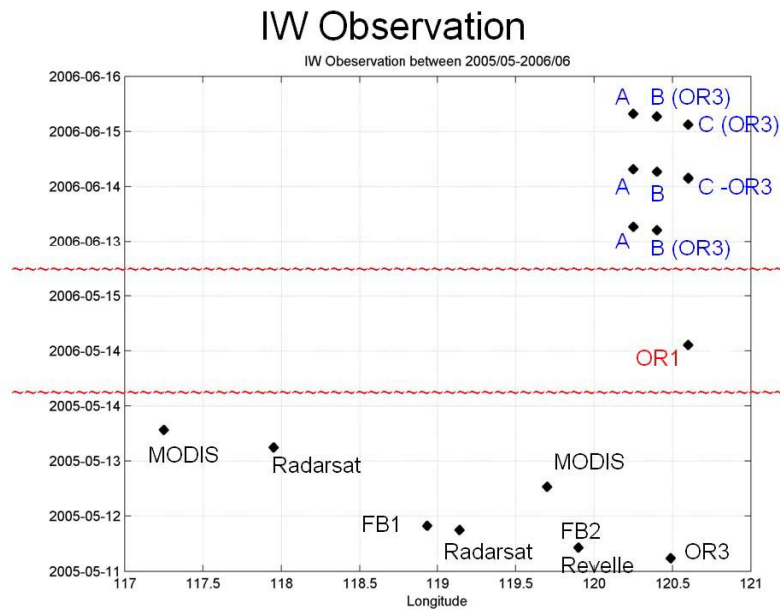
- (a) Analyze satellite images from satellite radar and optical sensors to locate the NLIWs in SCS as a function of time and location
- (b) Deploy several strings of temperature loggers (T-chain) to record the propagation path and evolution of NLIW in the SCS;
- (c) Jointly with ship-board sonars and moored current meters to study the generation mechanisms and timing of NLIWs in the Luzon Strait;
- (d) Install wave gauges on R/V Ocean Researcher 1 to collect the surface wave data, in concurrent with the collection of T-chain, ship radar and ADCP data;
- (e) develop models on the generation and propagation of NLIWs from Luzon Strait to SCS

## **WORK COMPLETED**

Before the start of this 3-year project, NLIWs in northern South China Sea were observed intermittently. To explain the intermittency and inhomogeneous distribution of these NLIWs in satellite Synthetic Aperture Radar (SAR) images of SCS, several hypotheses were proposed on their generation sites and the generation mechanism. Locating these NLIWs and tracing their source regions were the tasks of our first year project. The goal was accomplished, with the joint efforts of oceanographers from Taiwan, US, and the Philippines.

Two papers were published as the result of 2005 field experiment in April-May: R/V Roger Revelle, R/V Fishery Researcher 1, R/V Ocean Researcher 2, R/V Ocean Researcher 3, and two fishing boats shared the tasks. Several satellite images showed the location of NLIWs in near real time mode. It helped the field work for tracing the NLIWs with sonars and CTD, and for on-site observing NLIWs. From CTD and sonar data of upper layers, Klymak et al. (2006) inferred a deep-sea NLIW of 175 m amplitude in late April. Liu et al. (2006) found a deep-sea NLIW of 140 m amplitude on May. The joint cruise was very successful in finding the NLIW regularly, in recording the passing of the world most powerful NLIWs, and in providing enough information for the planning of the second year field work.

For the second year (2006), two cruises were carried out to map the evolution of NLIWs near their source region. In mid-May, most of the ship time was wasted due to the passing of the first typhoon of 2006, Janchu (Pearl). Despite the severe loss of ship time and moorings, we managed to collect some data from moorings and towed T-chain, ship radar and ADCP. The location and time of collected data are show in Fig. 1



***Fig. 1 The space-time distribution of collected data on NLIW of SCS.***

## PERSONNEL EXCHANGES AND TRAVEL COMPLETED

***Summary of personnel exchanges and travel conducted under this NICOP.***

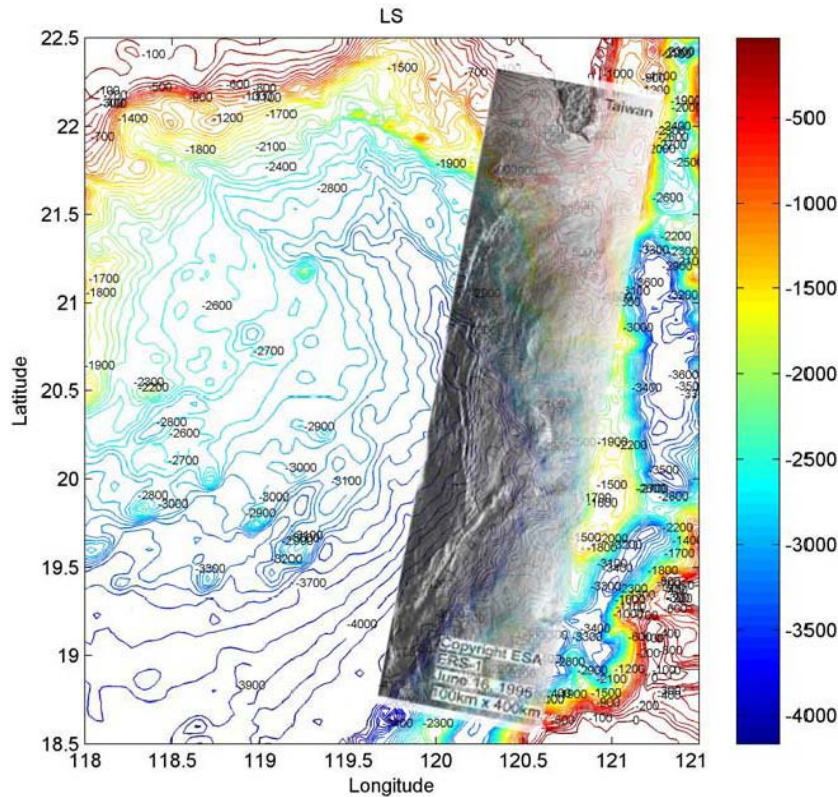
Name	Home Institution	Scientific / Technical Purpose of visit	Dates year/mm/dd
Cho-Teng Liu	NTU/ IO	1. consult Dr. W. Plant on the fine scale surface signature in coherence radar images, satellite images, ship radar images and T-chain data; exchanged data that are related to this topic  2. Present one paper in IGARSS 2006 (Denver)	2006/7/26-8/4
Cho-Teng Liu	NTU/IO	Attend PORSEC 2006 (Busan, Korea) to present result of NLIW studies	2006/11/1-4
Cho-Teng Liu Ming-Kuang Hsu	NTU/IO TSINT	Attend ONR PO06 NLIWI Meeting in Kaohsiung, Taiwan  Report progress through two poster presentations	2006/11/14-16

## RESULTS

### 1. Background on the project

Ebbesmeyer et al. (1991) hypothesized that the NLIWs in the northern South China Sea (SCS) originate from the sills between Batan Islands, just like the NLIWs of Sulu Sea originate from the sills between islands over the east side of Sulu Sea. This hypothesis has two major difficulties in explaining the NLIWs from Luzon Strait (LS) in SAR images. First, no other SAR image showed the same NLIW pattern between Hengchun Ridge and Batan Islands. Second, the general pattern of NLIW fronts NE of Dongsha Atoll (near 117E, 21N) is in the direction WNW, not northward as predicted by Ebbesmeyer et al. (1991).

The ERS-1 SAR image (Fig. 2) of non-linear internal waves (NLIWs) of Luzon Strait in 1995/6/16 shows quite different features like other NLIWs near Taiwan (Liu et al., 1994). Existing theories and experience were insufficient to explain the location, shape and size of NLIW in that SAR image.

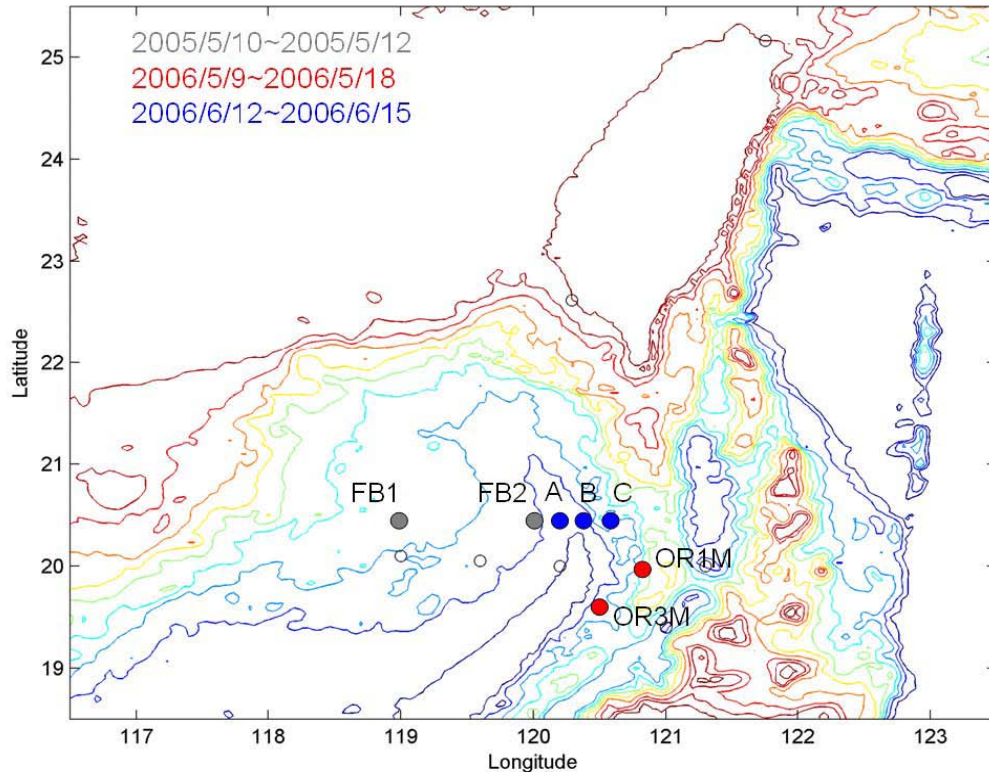


***Fig. 2 ERS-1 SAR image of 1995/6/16 showing NLIW in Luzon Strait, SW of Taiwan. The colored contour are depth in meters. NLIW fronts are parallel to 2000 m depth contour along the eastern slope of HengChun Ridge between Taiwan and Luzon in 19N~21.3N.***

In 2005 experiment, we demonstrated that Hengchun Ridge plays major role in the generation of NLIWs in SCS, and these NLIWs propagate at the speed about 2.9 m/s. The next question to be answered is the evolution of NLIWs, i.e. the location where internal tide (linear internal wave) evolves into 1 wave front, before evolving into 2 fronts at 120E.

## 2. Method of observation

The field and satellite observation program was designed to locate these NLIW as often as possible. It includes moorings of thermistors and SC-ADCP. Fig. 3 shows the location of moorings that were recovered in May 2006 (red dots) and in June 2006 (blue dots).



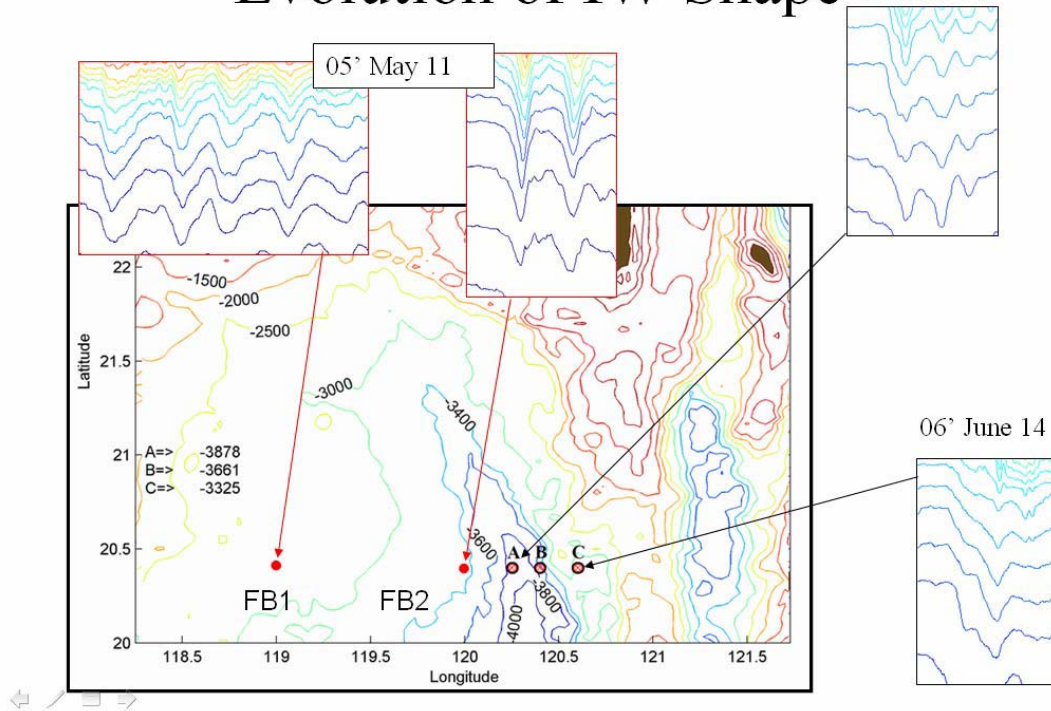
***Fig. 3 T-chain locations (color coded on the time of deployment) near the source of NLIW, Hengchun Ridge along 121E.***

The first typhoon of 2006, Janchu (Pearl) was formed after we deployed four moorings on May 12. Although the probability for typhoon to hit Taiwan is less than 10% in May, Janchu did make a turn and passed by our moorings towards Taiwan. This resulted the loss of two moorings. For the second cruise in June of 2006, we deployed three T-chains and lost one due to failure of deck gear of R/V OR3.

To study the evolution of NLIWs from Luzon Strait, our moorings (T-Chain and SCADCP) were placed near the source of NLIW, Hengchun Ridge (HCR). According to the analytical solution of NLIWs (Apel, 2003), non-linearity of internal waves increases as they leave the source region HCR along 121E, and NLIWs was formed gradually as the linear internal wave propagates westward from LS, and the number of NLIW fronts increases. At station OR1M (in Fig. 3), no NLIW was observed. Startig at station C (in Fig. 3), NLIWs gradually evolve. Fig. 4 summarize the waveform of NLIWs that we observed in 2005 and 2006.

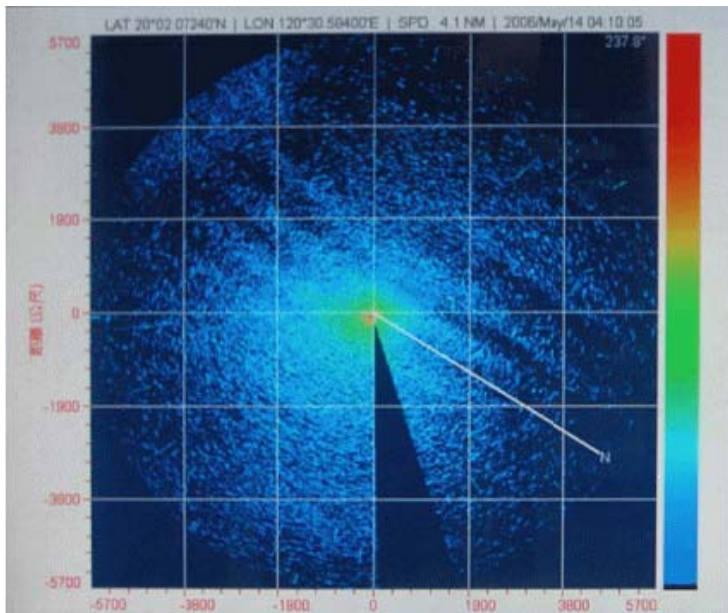


# Evolution of IW Shape

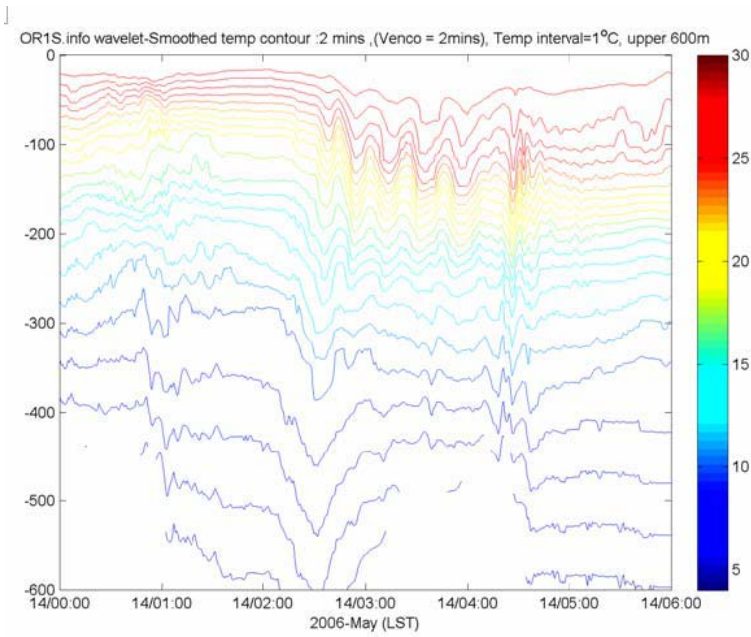


**Fig. 4** The wave form of NLIWs as a function of longitude. They clearly shows the evolution process as described by Apel (2003)

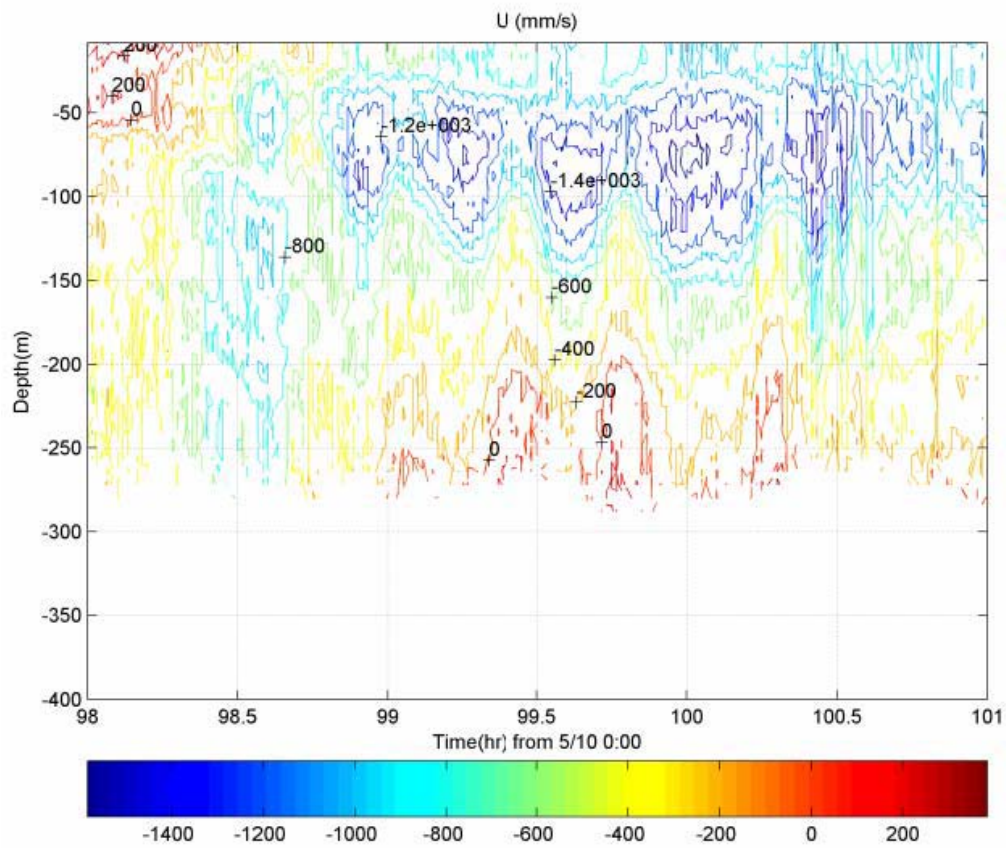
At (20.4N, 120.5E), R/V OR1 observed a train of small internal waves that follow the giant NLIW were also found in ship radar images (Fig. 5), T-chain data (Fig. 6), and in ADCP data (Fig. 7). They trail the giant NLIWs (traveling at 2.9 m/s) with propagation speed about 1.7 m/s.



**Fig. 5** Ship-radar image of small linear internal waves (LIW). A packet of waves that was observed by ship radar on R/V Ocean Researcher 1, at 20:11 UTC of 2006/5/13 (white line is to the north).



**Fig. 6** *T-chain data show the movement of isotherms as NLIW passing a T-chain that was towed behind R/V OR1.*



**Fig. 7** *ADCP data show the small linear internal waves that trailed the NLIW*



### 3. Conclusions

After confirming the existence of NLIWs in SCS, we were able to pin-point the region where linear internal wave evolves into NLLIW. Their waveforms were also mapped with moored and towed T-chains. A train of small internal waves that follow the giant NLIW were also found in T-chain data, ship radar images, and in ADCP data. They trail the giant NLIWs (traveling at 2.9 m/s) with propagation speed about 1.7 m/s.

### IMPACT/APPLICATIONS

This year's field observation further enhanced our confidence that Hengchun Ridge plays the major role of generating NLIWs in northern South China Sea, more than other possibilities, Batan Islands, the baroclinic instability of Kuroshio boundary and other sources. The generation of NLIW over Hengchun ridge may asymmetric, because no NLIW was observed east of Hengchun Ridge, neither by satellites, nor by in situ observations. With sufficient knowledge of NLIWs propagation in the deep SCS, the generation and evolution process of NLIWs near Hengchun Ridge shall be the target of next year's field experiment for a closer look, if there are no more typhoons.

### RELATED PROJECTS

Prof. Rob Pinkel and Prof. Jody Klymak an ONR Project to study the NLIW with Fast CTD and deep sonar to map the generation, evolution and propagation of NLIW in SCS.

Prof. Steve Ramp leads ONR project named WISE that studies NLIWs in the northern SCS with mooring observations,

### REFERENCES

Apel, J. (2003) A new analytical model for internal solitons in the ocean. *J. Phys. Oceanogr.*, 33, 2247-2269

Armi, L. and D. Farmer 2002. Stratified flow over topography: bifurcation fronts and transition to the uncontrolled state. *Proc. R. Soc. Lond. A* (2002) **458**, 513-538

Bole, J. B., C. C. Ebbesmeyer, and R. D. Romea, 1994. "Soliton Currents in the South China Sea: Measurements and Theoretical Modeling", Paper *OTC 7417*, presented at the 1994 Offshore Technology Conference, Houston, Texas, May 2-5, 1994, 367376.

Cummins, P, S. Vagle, L. Armi and D. Farmer 2003. Stratified flow over topography: upstream influence and generation of nonlinear internal waves. *Proc. R. Soc. Lond. A* (2003) **459**, 1467-1487

Ebbesmeyer, C.C., C. A. Coomes, and R. C. Hamilton, K. A. Kurrus, T.C. Sullivan, B. L. Salem, R. D. Romea, and R. J. Bauer 1991. "New Observations on Internal Waves (Soliton) in the South China Sea Using an Acoustic Doppler Current Profiler", *Marine Technology Society 91 Proceedings*, New Orleans, 165-175.

Farmer, D. and L. Armi 1999. Stratified flow over topography: the role of small-scale entrainment and mixing in flow establishment. *Proc. R. Soc. Lond. A* (1999) **455**, 3221-3258

- Farmer, D. and L. Armi 2001. Stratified flow over topography: models versus observations. *Proc. R. Soc. Lond. A* (2001) **457**, 2827-2830
- Hsu, M.K. and A. K. Liu 2000. "Nonlinear internal waves in the South China Sea", *Canadian Journal of Remote Sensing*, **26**, 2, 72-81.
- St. Laurent, L.C., S. Stringer, C. Garrett, D. Perrault-Joncas, 2003. The generation of internal tides at abrupt topography. *Deep-Sea Research I*, **50**, 987–1003.
- Klymak, J. M., R. Pinkel, Cho-Teng Liu, A. K. Liu, and L. David (2006), Prototypical solitons in the South China Sea. *Geophys. Res. Lett.*, 33, L11607, doi:10.1029/2006GL025932
- Liu, A. K., J. R. Apel, and J. R. Holbrook 1985. "Nonlinear internal wave Evolution in the Sulu Sea", *Journal of Physical Oceanography*, **15**, 1613-1624.
- Liu, Cho-Teng, R. Pinkel, M-K Hsu, J.M. Klymak, H-W Chen, C. Villanoy (2006) Nonlinear Internal Waves from Luzon Strait. *EOS*, 87(42), 449-451
- Niwa, Y., and T. Hibiya, 2001. Numerical study of the spatial distribution of the M2 internal tide in the Pacific Ocean. *Journal of Geophysical Research*, **106**, 22229– 22441.
- Pinkel, R., W. Munk, P. Worcester, et al., 2001. Ocean mixing studied near the Hawaiian Ridge. *EOS Transactions of the AGU*, **81**, 545,553.